Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

3D Integrated Sensing Solutions

Fermilab: A. Apresyan, R. Lipton, D. Braga, F. Fahim

SLAC: A. Schwartzman, C. Kenny, J. Segal, A. Dragone, L. Rota

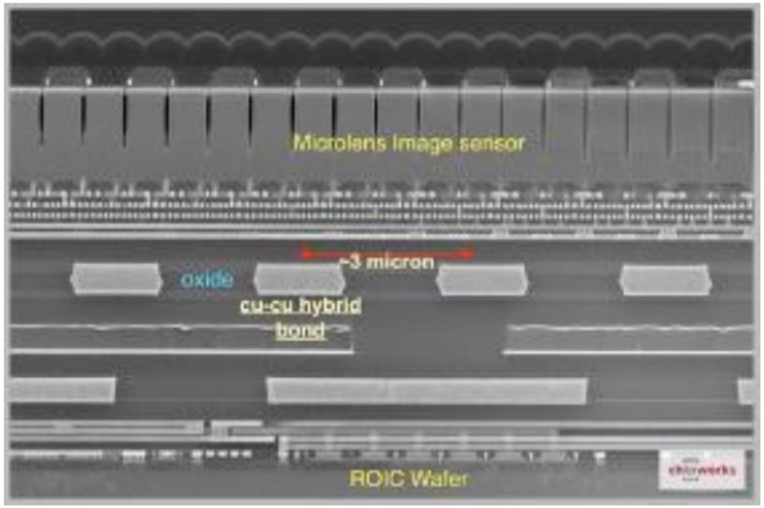
LLNL: A. Carpenter

CPAD 2023

08 November 2023

Objectives

- Development of low-power, highly granular detectors in ($\vec{x}$, t)
  - Required to achieve breakthroughs across HEP, NP, BES, and FES
  - Adoption of 3D-integration has been cost-prohibitive in academia
- Supported by DOE "Accelerated Innovation in Emerging Technologies"
  - Joint development effort of SLAC and FNAL teams
  - Partner with industry leaders to implement new technologies
  - Design goal is to achieve position resolution ~5 µm, timing ~ 5-10 ps



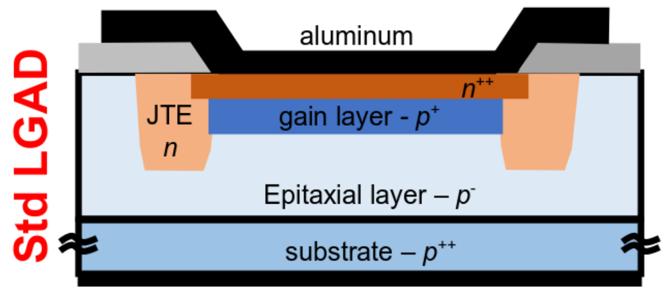
Fermilab

Objectives

- The research program consists of three main thrusts towards developing the proposed detector:
  - **Thrust 1:** *Design and manufacture Low-Gain Avalanche Diodes (LGADs) devices compatible with 12’’ foundry processes*
  - **Thrust 2:** *Design application specific integrated circuit (ASIC) techniques to meet various application needs for granularity, precision timing, and power*.
  - **Thrust 3:** *Enable a new generation of particle detectors that utilize 3D-integration, combining state-of-the-art 12” wafers from different foundries*.

Low Gain Avalanche Diodes (LGADS)

Recently there has been intense interest in Particle Physics and beyond in applications of LGADs

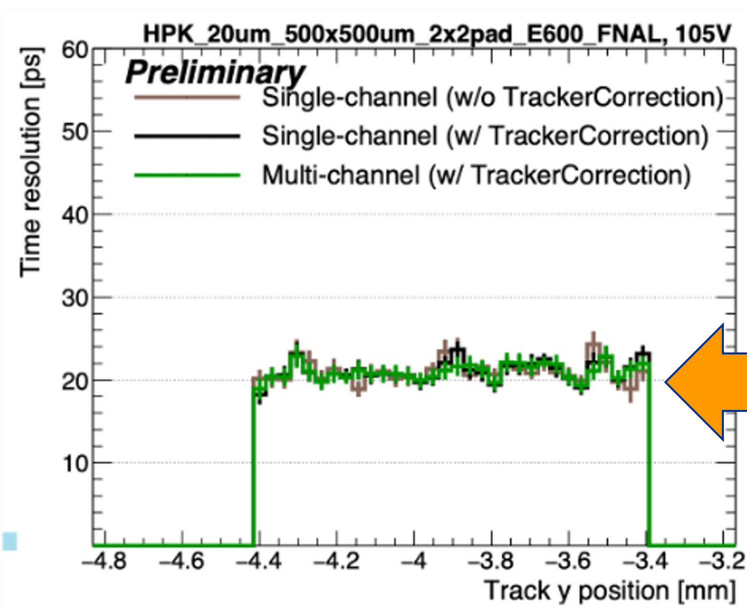


Single LGAD pixel

- Avalanche diodes with modest (10-20) gain that provide excellent timing resolution
- Typical devices to date have been dedicated sensors with reach through implants bump bonded to readout.
- Limited fill factor due to field termination
- Compelling variants have begun to emerge with AC coupling, improved radiation hardness and buried implants
- We are interested in expanding the concept to a CMOS process

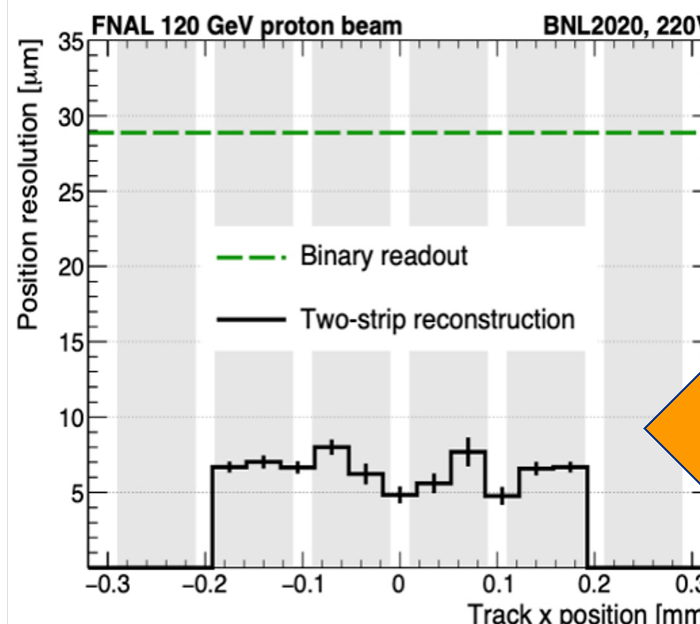
Applications in High Energy Physics (HEP)

- CMS and ATLAS are building first-generation detectors
  - Very coarse position resolution, around 30-40 ps timing
- First demonstration of simultaneous ~5 µm, ~30 ps resolutions with AC-LGADs beam: technology for 4D-trackers!



20 ps time resolution

Hamamatsu 20 µm AC-LGAD sensor



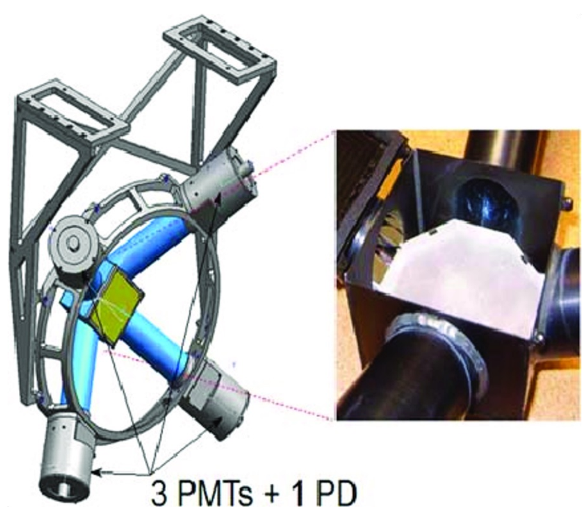
~5 µm positic resolution

BNL AC-LGAD sensor

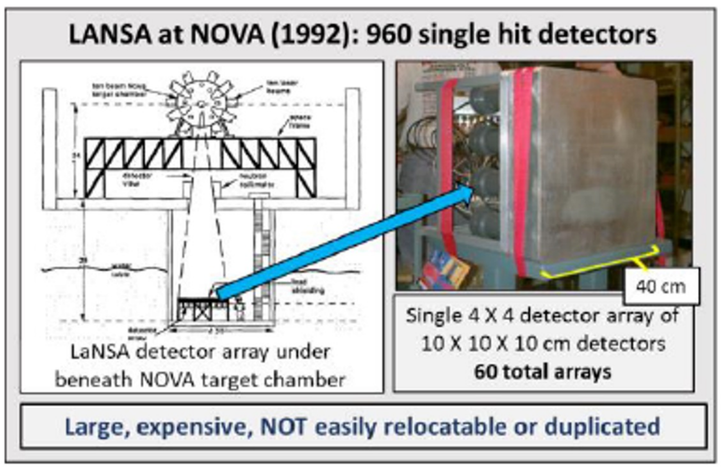
Applications in Nuclear Fusion Energy Research

- Exciting results recently at LLNL Ignition Facility
  - Net energy gain fusion reaction achieved
- Neutron spectrometers and low signal high speed imaging
  - Neutron spectrometer using time stamping single hit detector
  - Neutron TOF detectors need wider dynamic range

Current nTOF uses 4-PMTs



PMT based TDC system was built in the 90s

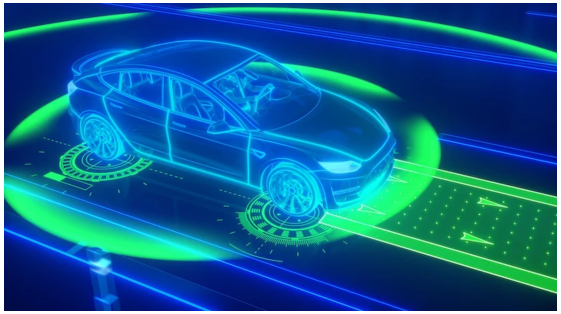


M. B. Nelson, M. D. Cable; LaNSA: A large neutron scintillator array for neutron spectroscopy at Nova. Rev. Sci. Instrum. 1 October 1992; 63 (10): 4874–4876. https://doi.org/10.1063/1.1143536

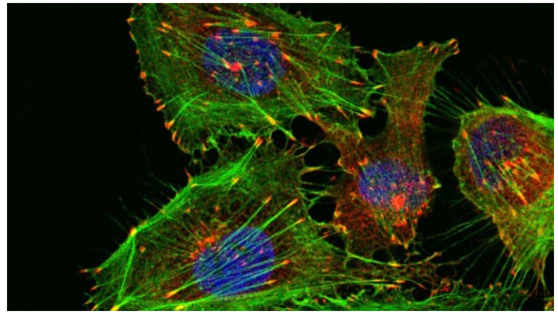
Applications in X-RAY Science

- Development of large area camera systems for deployment at DOE Photon sources such as LCLC II at SLAC
- Impact: pharmaceuticals, batteries, photo-voltaics, quantum science, materials science
- Soft X-ray imaging: gain improves signal-to-noise for soft x-rays
- X-ray Photo-Correlation Spectroscopy
- Mossbaeur Spectroscopy
- X-ray spectroscopy
- Momentum Microscopy

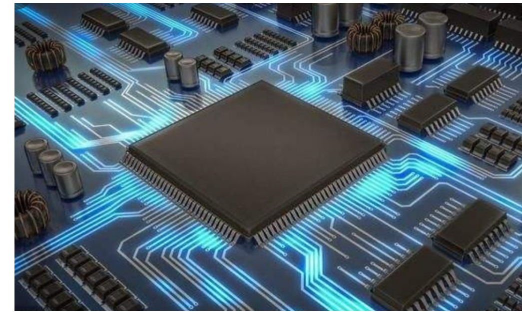
Other applications



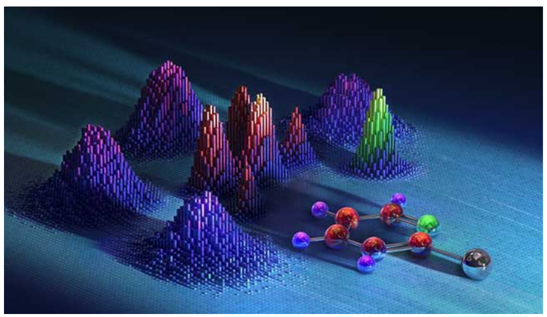
Lidars and Automotive



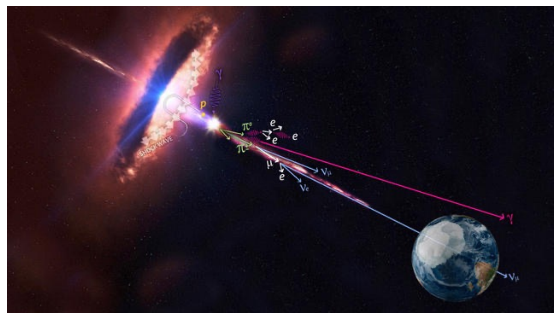
Bio Imaging and Life Science



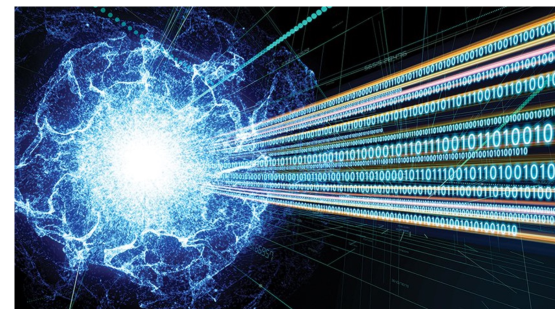
Fast timing applications



Coulomb explosion imaging



Astro-particle physics

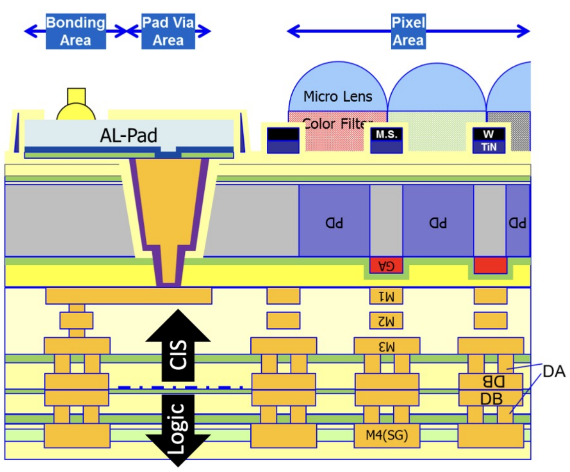


Quantum science and cryptography

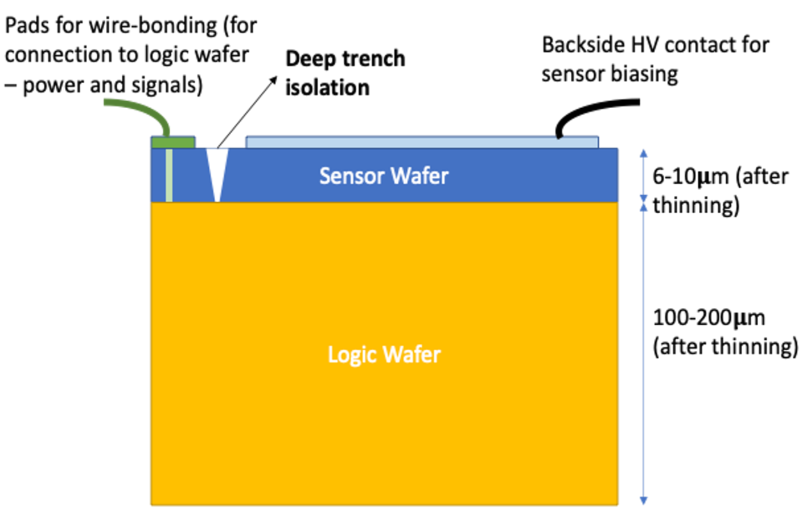
Advanced manufacturing

Development of sensors

- Produce sensors on 12” wafers with a commercial partner
  - Process is a 10 µm epi; 130-150 Ohm-cm resistivity
- We performed simulations to study the feasibility of both gain and timing performance using vendor’s parameters

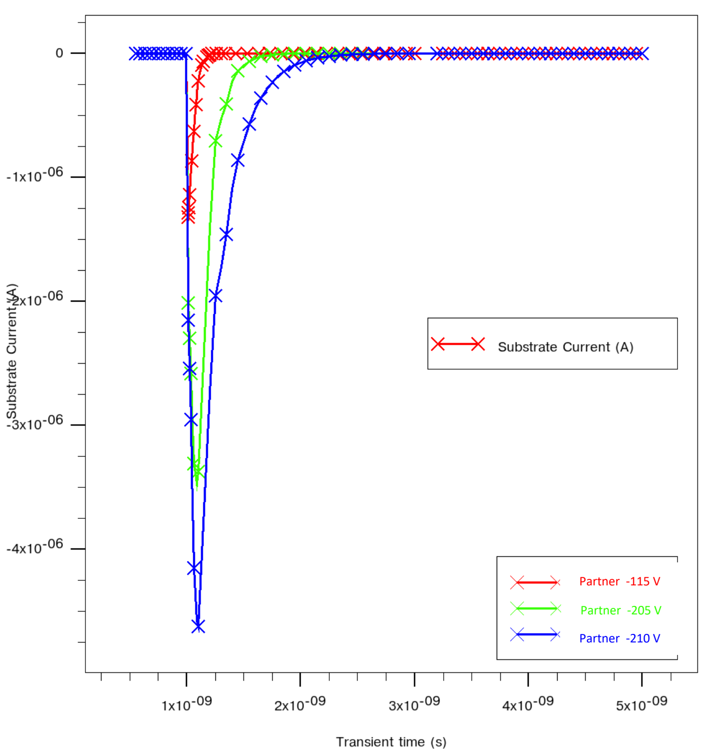


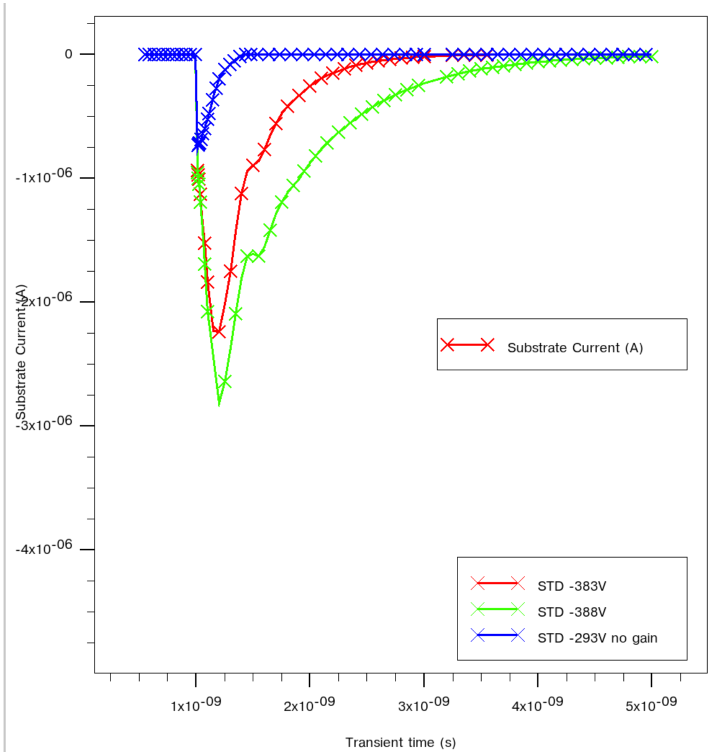
Our DRM supports down to 2.5um pitch



Fermilab

Pulse simulations

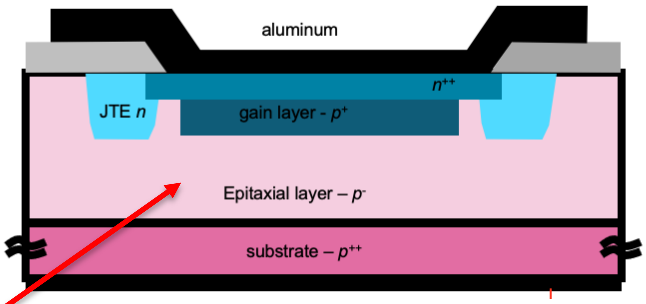


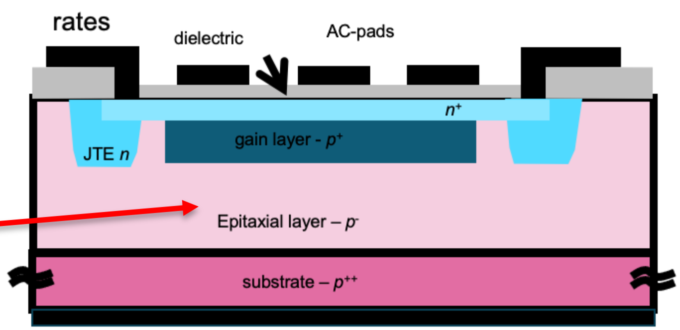


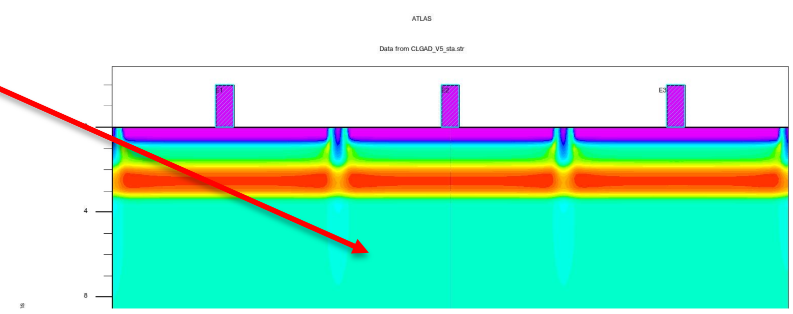
- Simulations of a “standard” LGAD and partner’s 65 nm process.
  - ”Standard” process - 20 µm thick high resistivity
  - “Partner” process - 10 µm thick, moderate resistivity
- Signals from “partner” process are narrower and faster rise time

Additional processing

- The basic functionality of the device looks good with 10 μm epitaxy.
- Additional structures are needed for a working device:
  - DC LGAD: ”standard” devices
  - AC LGAD: 100% fill factor, good position resolution
  - Deep junction LGAD: for higher radiation hardness







Fermilab

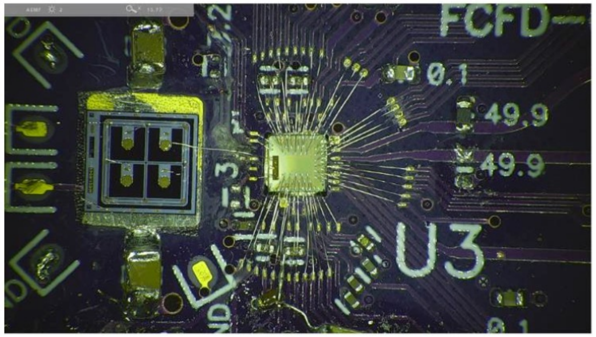
Development of ICs

- Many commonalities among specifications for HEP, NP, BES or FES applications
  - Work together to develop IC techniques and prototypes to meet specific application requirements

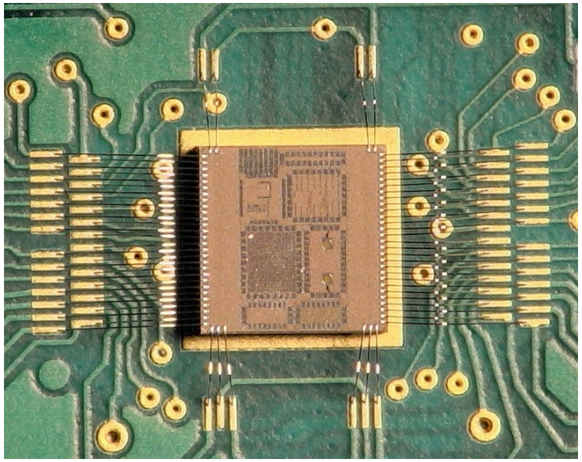
HEP Application	Pitch Range	Time Resolution	Power	Noise - ASIC	Frame Rate	Gain
e+ e- collider	~ 1 mm	< 10 ps	~1 W/cm²	n.a.	Circular ~50MHz Linear 120Hz-300MHz	~10
Proton or muon collider	< 25 μm	< 10 ps	~1 W/cm²	n.a.	40 MHz	~10
BES Application	**Pitch Range**	**Time Resolution**	**Full Well**	**Noise - ASIC**	**Frame Rate**	**Gain**
Soft x-ray imaging	100 μm	n.a.	> 100 keV	< 1 keV	< 1 MHz	> 5
Mossbaeur Spectroscopy	100 μm	< 5 ns	> 1 MeV	< 4 keV	< 1 MHz	> 5
X-ray Spectroscopy	> 100 μm	n.a.	< 20 keV	< 100 eV	< MHz	20
Momentum Microscope	100 μm	< 100 ps	> 30 keV	< 1 keV	1 MHz	20
FES						
LCLS Pulse Train	100 μm	< 350 ps	> 3 MeV	< 2 keV	>3 GHz burst	3-5
NIF	< 100 μm	< 20 ps	> 10 MeV	< 3 keV	>50 GHz burst	~10

Development of ICs

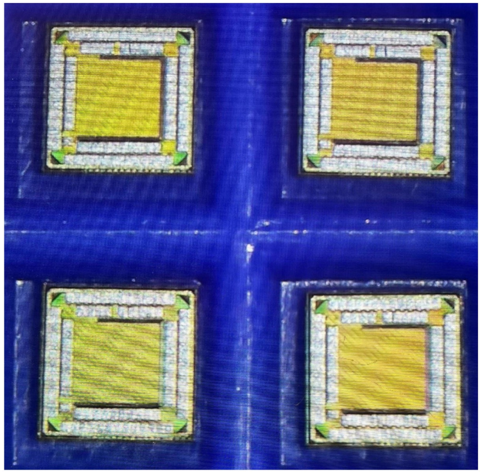
- During the 1st stage we will optimize and produce ASIC prototypes on MPW runs to identify the best solutions
  - **Technology**: the HEP community's choice for the future 28 nm
  - **Low Noise Amplifier**: tuned for capacitances of smaller pixels
  - **Discriminator:** Design simple and robust discriminator for low-power
  - **TDC**: dominant consumer for small pixels, need innovative solutions



FCFDv0 pre-amp + discriminator



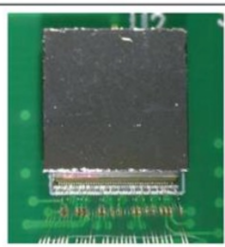
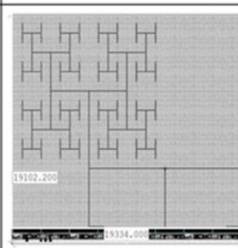
FNAL TDC



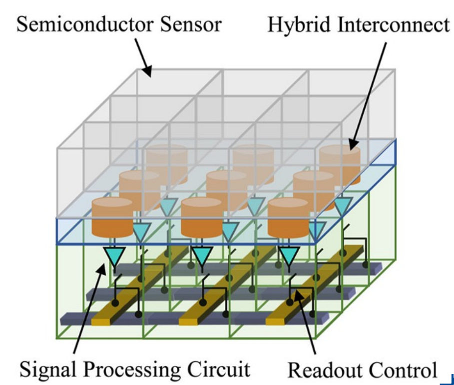
SLAC TDC

Development of ICs

- **Designs for BES applications**
  - The principal difference of applications is a requirement to also measure the deposited energy for soft X-ray imaging
- **Designs for FES applications**
  - Inertial Confinement Fusion (ICF) experiments measure peak plasma burn durations below 100 ps: need to sample with precision ~10 ps
  - X-ray imaging requires full 2D image samples over this burn history

	SparkPix-ED	SparkPix-RT	SparkPix-T	SparkPix-S
Front-end	energy	energy	timing	energy
Information extraction	triggering	data compression	sparse readout	sparse readout
Frame-rate	1 MHz / 100 kHz CW	100 kHz	1 MHz	1 MHz
Picture / Layout				

hCMOS UXI Sensors coupled with LGADs could open up many low energy/low signal high speed imaging applications



Summary

- Project funded for a 2-year duration
  - Develop LGADs capable 3D integration with 28nm CMOS foundry technology
  - Implement 28nm MPW runs for ASIC development
  - LGAD run will include structures for bump-bonding to ASIC, and process structures needed for 3D integration
- In the following years we will apply for follow-on project with full 3D integration using 12” 28nm CMOS wafers